Plan and Progress on Experimental Validation of Computational Small Rotor Design Optimization Tools

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Advanced Air Mobility (AAM) Challenge

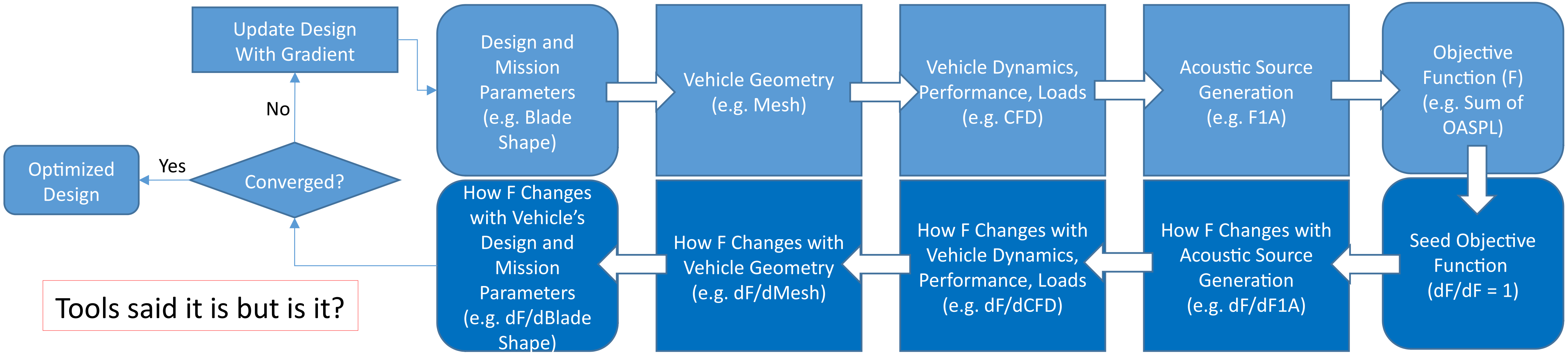
- Opportunities of AAM vehicles are numerous
  - Large sized vehicles for intraregional transportation
  - Medium sized vehicles for urban and rural applications (UAM)
  - Small sized vehicles for package deliveries and surveillance (sUAS)
- AAM challenges aeronautics community with unique challenges in performance and community impact
  - Safety
  - Reliability
  - Automation
  - Community impact (noise)

AAM Challenge

- Traditional large transport vehicles limit design opportunities
  - Tube and wing
- Large helicopters and multirotor vehicles do have design opportunities but are limited also
  - Traditional main/tail configurations
  - X-rotors, tandem, etc.
- AAM vehicles offer significantly more design opportunities
  - Rotor count, placement, blade count, rotation direction
  - Wing design and placement, installation effects
  - Blade shape and rotor sizing
- AAM vehicles also have significantly different flight mission requirements
- Offers opportunity to design from the ground up
- What can our design tools predict, what do our design tools miss?
  - Do validation data exist?

Design Optimization

- Many ways to optimize design for increased performance and/or reduced community impact
  - Genetic algorithms, neural nets, gradient based, etc.
- Adjoint based design optimization and backwards differentiation allow for much finer grain
  - Perfect for small number of objectives (noise metric) with many design variables
    - Design variables: blade shape, installation parameters, mission performance requirements, mission flight paths, etc.
  - Can incorporate constraints (performance)
  - Challenging to do integer optimizations (such as rotor count)
  - Can (with adequate computational effort) do installation effects
- Design optimization procedure:



Tools said it is but is it?

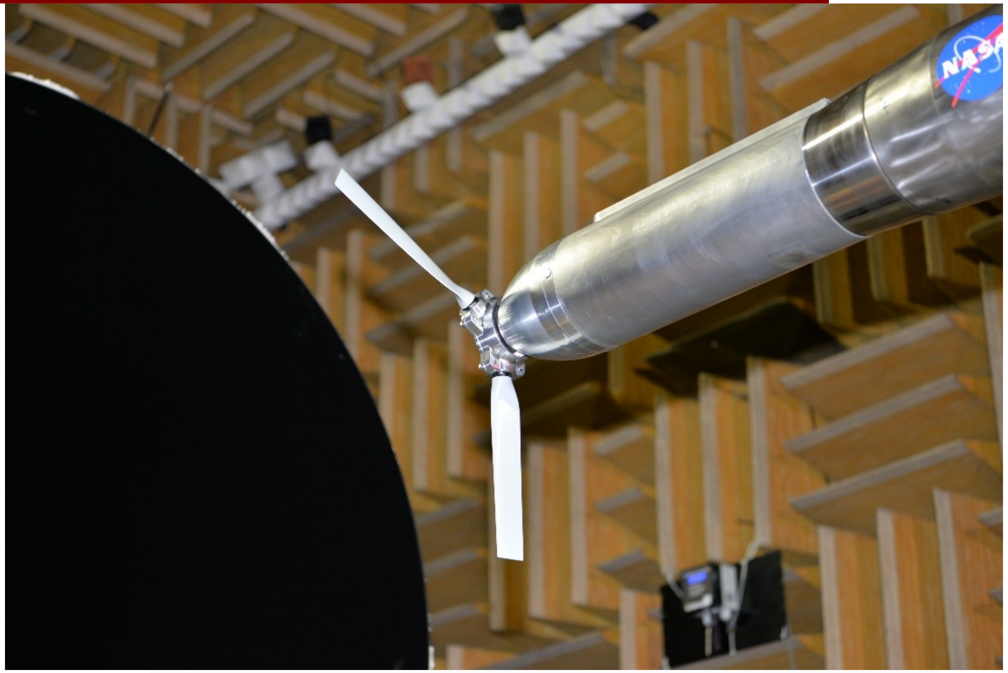
Objective

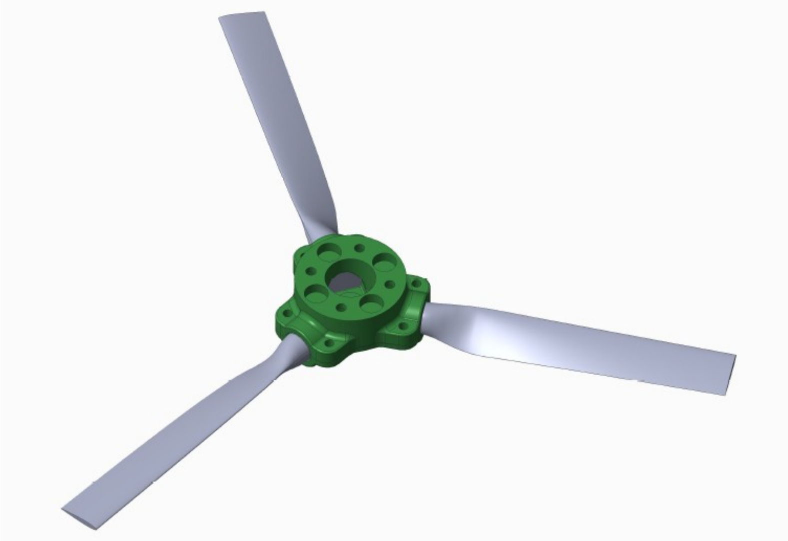
- Validate computational optimization design tools
  - Noise measurement and computation (multiple rotors, installation, etc.)
  - Mission from takeoff to landing (community impact objective)
  - Must have measurement data set of baseline configuration (starting point)
- Process of validation
  1. Select baseline configuration geometry and measurement data
  2. Validate our tools against baseline configuration data
  3. Run design tools to get optimized designs with performance constraints
  4. Fabricate optimized designs
  5. Test optimized designs under same conditions to see predicted improvement
- What available data can be used as starting point
  - Limited full-scale data, restricted to isolated rotor at this time
  - Noisy rotor in a repeatable environment
  - More than one flight condition
  - Array of microphones for multiple emission angles (long duration flight)

Available LSAWT Data

- Helically Twisted Rotor (HTR) aka C24ND
  - Used for checkout of Propeller Test Stand (PTS)

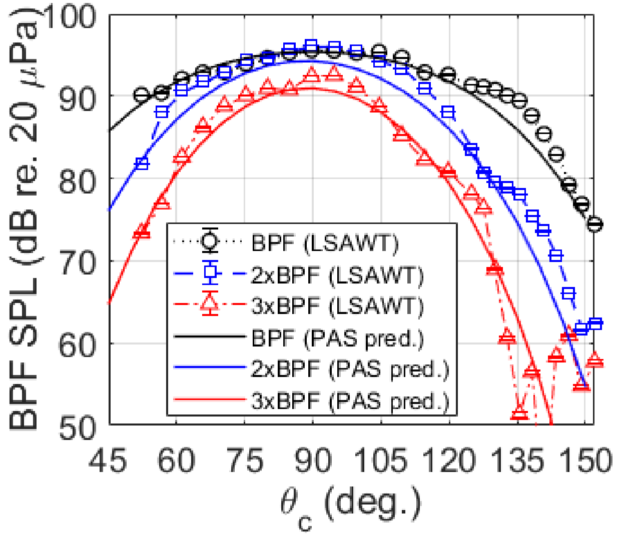
  - D = 24” (prop diameter)
  - P = 16” (prop pitch)
  - C = 1.5” (constant chord length)
  - NACA 0012 airfoils
  - Measurement data for multiple flight conditions
- This is a very noisy rotor



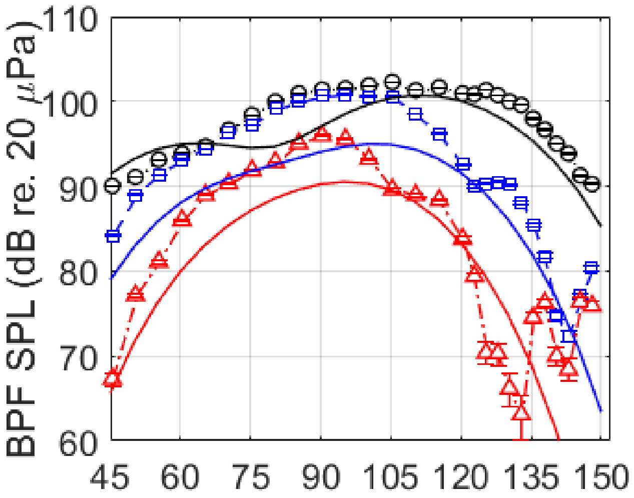


Helically Twisted Rotor (HTR) Data

- Forward Flight Condition:
  - (22 lbs.)
  - .2 Nm (72.2 in-lbs.)



- Hover Condition:
  - (59.1 lbs.)
  - 16.3 Nm (144 in-lbs.)

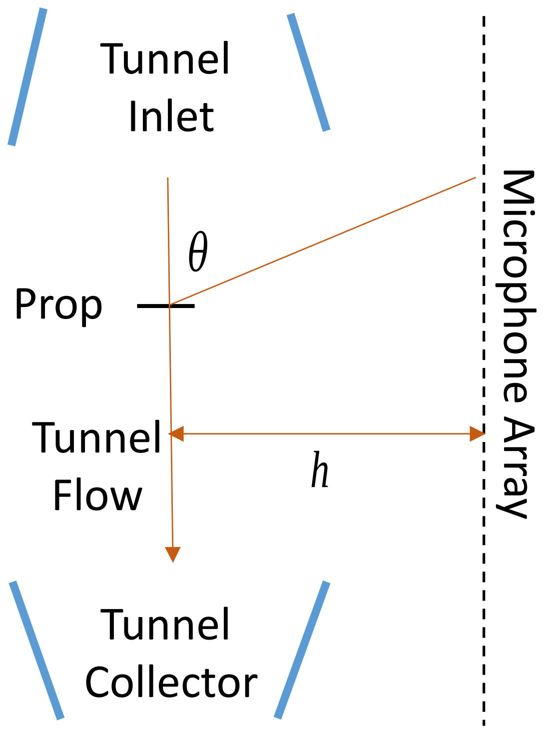


- Preliminary Data and Predictions:
  - Some thermal drift in thrust measurement may be present
  - Recent improvements to PTS improves thermal drift resulting in more accurate load measurements
  - ANOPP PAS has some difficulty predicting separation for hover condition
- Credit Nikolas Zawodny

Objective Function

- Incorporate as much as possible into objective function
  - Only have isolated rotor data
  - More than one flight condition to simulate maneuver
  - Directivity to simulate flyover and multiple observers
  - Frequency weighting to simulate human response
  - Performance constraints (not shown)
    - Optimized design must generate same thrust
    - Optimized design torque cannot increase

LSAWT (not to scale)



Integrate mean square pressure fluctuations over microphone array
Directivity limits () are functions of tunnel speed

$$F = 10\log_{10}\left(\int_{\theta_{l,ff}}^{\theta_{h,ff}} \frac{\langle p^2\rangle_{A,ff}}{\sin(\theta)}\,d\theta\right) + 10\log_{10}\left(\int_{\theta_{l,h}}^{\theta_{h,h}} \frac{\langle p^2\rangle_{A,h}}{\sin(\theta)}\,d\theta\right) - 20\log_{10}\left(\frac{p_{\mathrm{ref}}^2}{2\pi h^2}\right)$$

Forward Flight

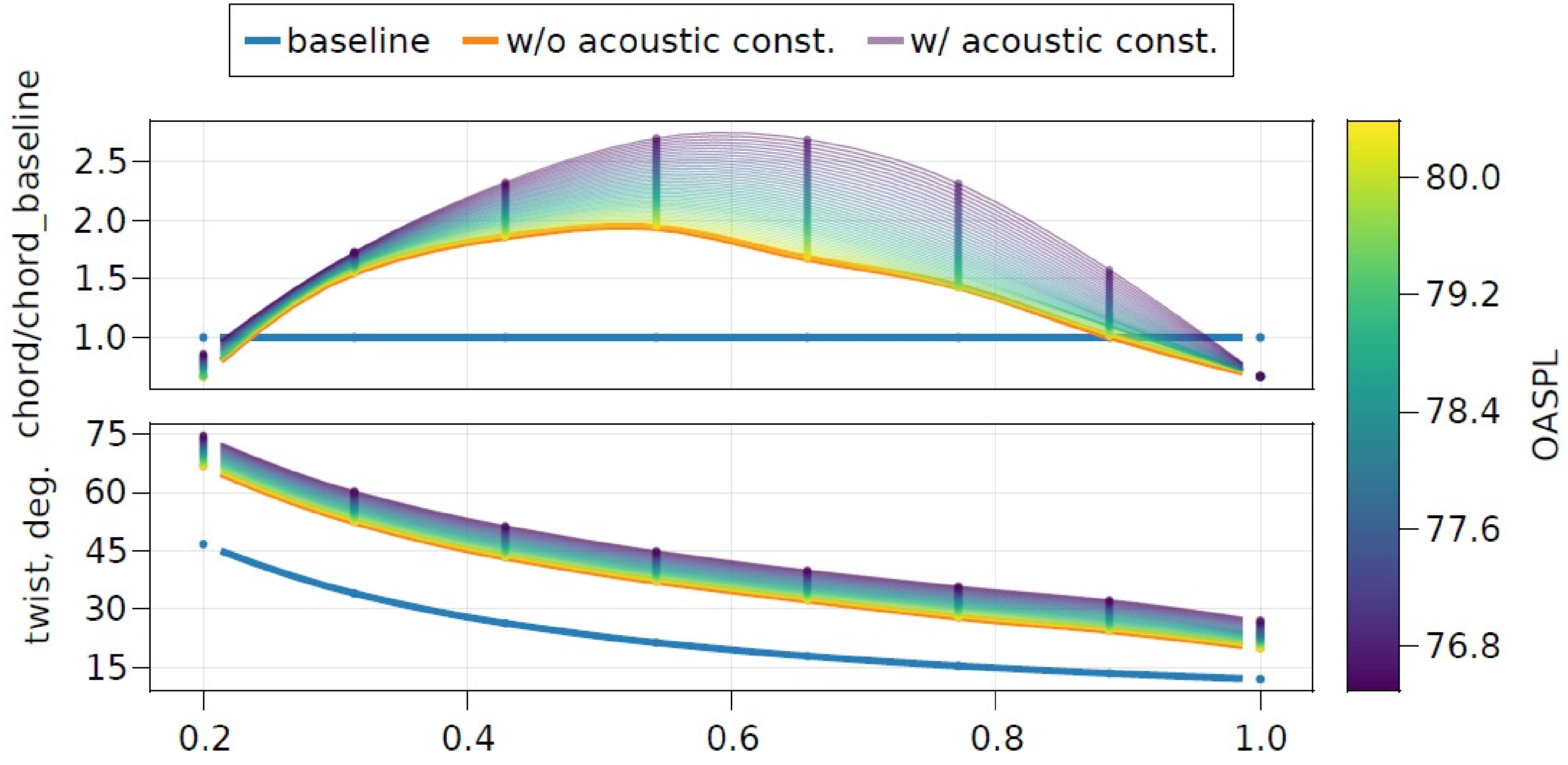
Hover

Optimization Tools

- Two tool fidelities
  - Low granularity / fast computation (BEMT)
  - High granularity / computationally intensive (CFD)
- Four optimization tool approaches
  - CCBlade.jl - BEMT code with compact acoustic sources
  - ABEAT - BEMT code with compact/noncompact acoustic sources
  - FUN3D - Unstructured CFD code
  - SU2 - Unstructured CFD code

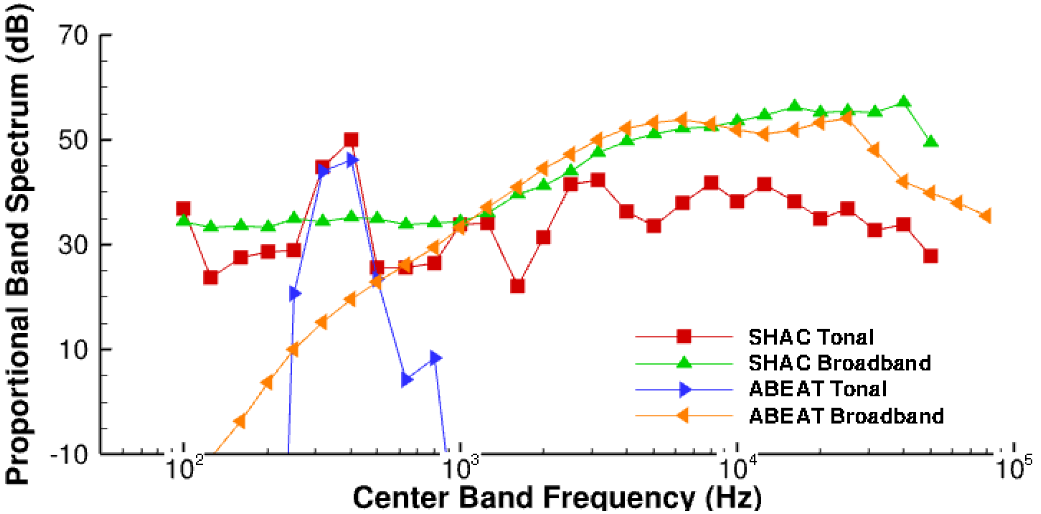
CCBlade.jl

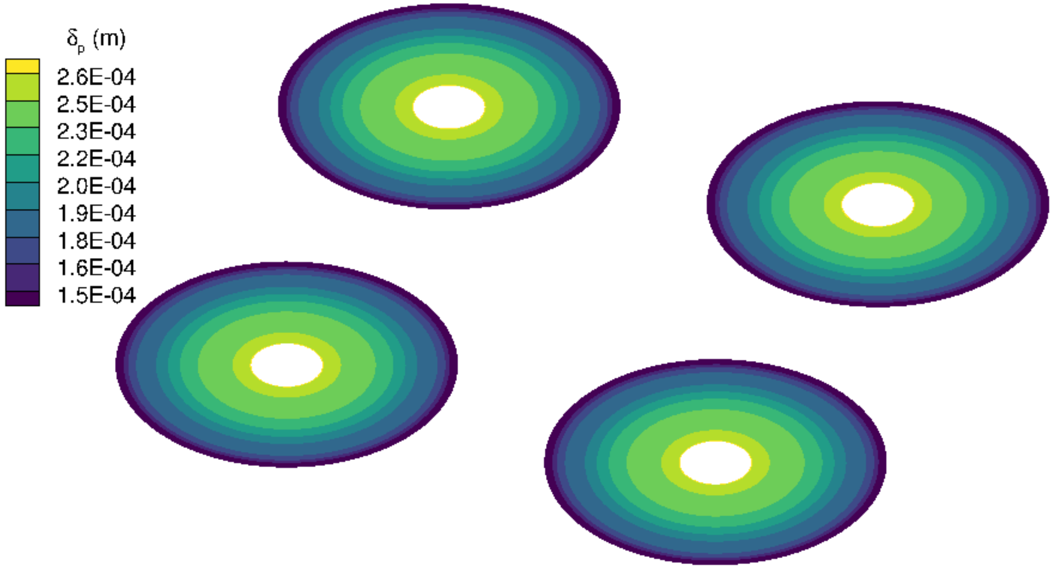
- Blade element momentum theory (BEMT)
  - Compact formulation of F1A
  - Very fast approximation of the noise
  - Simple approximation of blade shape influence on airfoil section lift and drag
- Much more detail and preliminary results in Dan Ingraham's talk following this talk



ANOPP2's Blade Element Acoustic Tool (ABEAT)

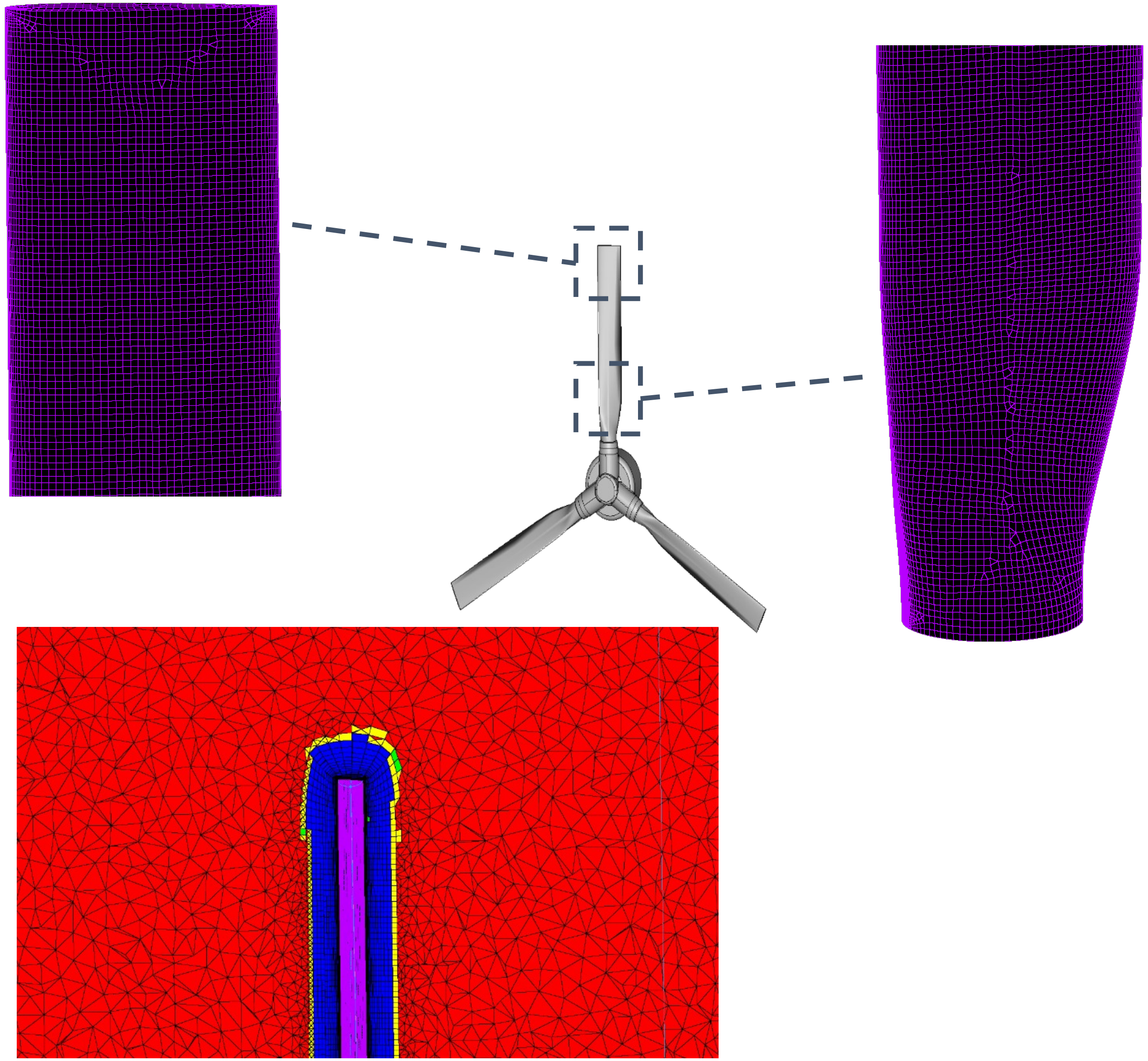
- Capability
  - Fast computation of noise from vehicle with single (helicopter) or multirotor (GL-10)
  - Each rotor may have similar airfoil geometry but may differ in RPM, phase offset, inflow, rotor angle of attack
  - Use linear inflow models (such as uniform, Pitt-Peters, etc.) but may also couple with user specified inflow
  - Include empirical broadband noise prediction (define boundary layer conditions and noise predictions)
  - No trimming, kinematics of propeller/rotor blades are fixed pitch (currently)
  - Only compact sources for tonal noise (currently, will be updated with next iteration)
  - Motor noise when ready
- Available in ANOPP2v1.3





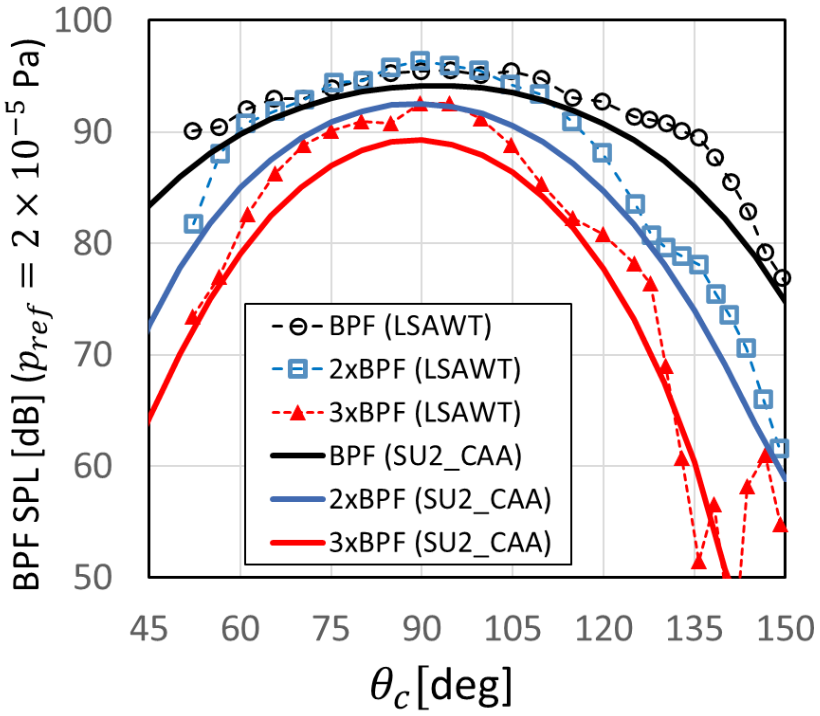
FUN3D CFD Solver

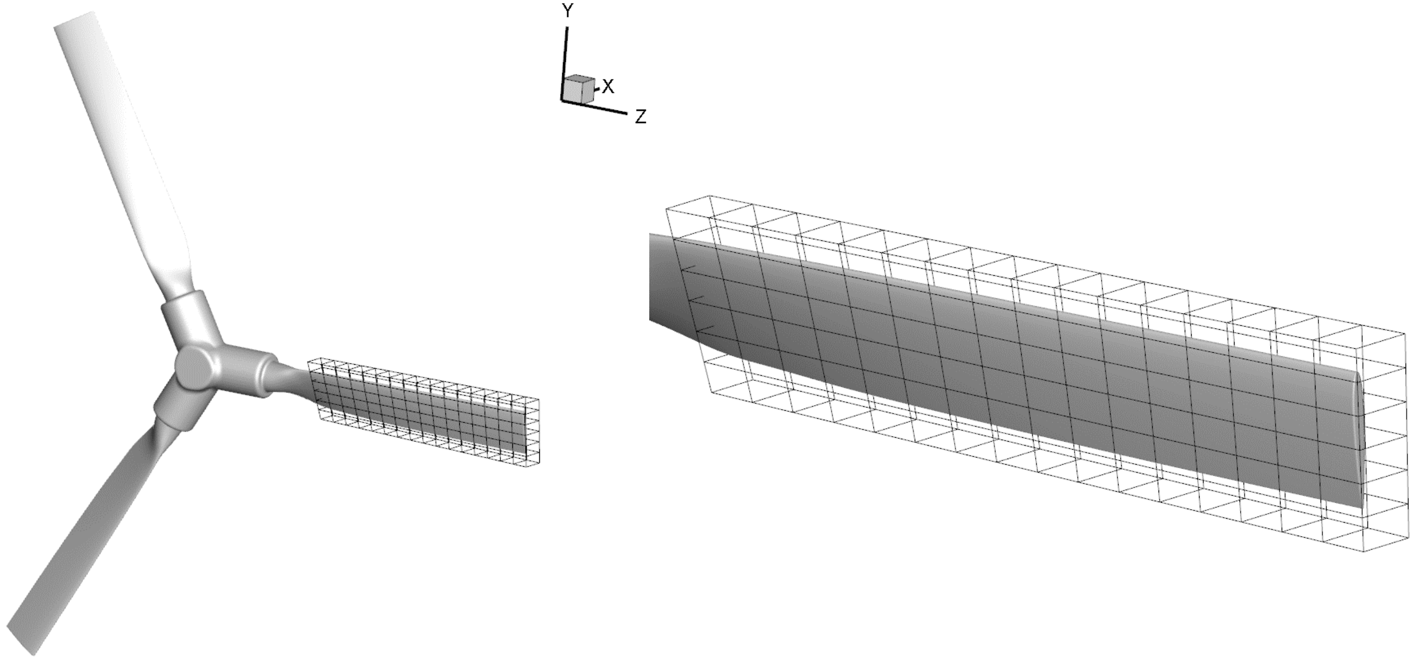
- Physical time stepping:
  - 2^{nd} order in time (BDF2OPT)
- Spatial differencing
  - 2^{nd} order row upwind for inviscid terms
  - 2^{nd} order central differencing for viscous terms
- Turbulence model
  - Spalart-Allmaras one-equation model
- Unstructured overset grids
- Steady and unsteady Predictions
- Adjoint capable



SU2 CFD Solver

- "Stanford University Unstructured (SU2)" is an open source PDE solver
- Active developer base around the world with many applications
- Adjoint-based capable for design
- Vertex-based, unsteady Reynolds-Averaged Navient-Stokes (URANS)





Current Status and Plan Moving Forward

- Currently validating acoustic prediction of baseline design
  - Each of four methods at different stages of validation
  - Some methods have produced optimized designs with some success
  - Have not incorporated full objective function
  - Some code development still underway
- Hope to have several optimized candidates by early summer
  - Currently have a few designs that can be fabricated but not final
  - New designs ready to fabricate by early summer
  - Placed in LSAWT in late summer / early fall
  - Maybe present preliminary comparisons at fall ATWG

Personnel

- Justin Gray (NASA Glenn)
  - Leading Multidisciplinary Design Optimization (MDAO) effort
- Daniel Ingraham (NASA Glenn)
  - Acoustic optimization using CCBlade.jl (following presentation)
- Douglas Nark (NASA Langley)
  - FUN3D design optimization
- Oktay Basal and Omur Icke (ODU) with Boris Diskin (NIA)
  - SU2 design optimization
  - Special thanks to Beckett Zhou of TU Kaiserslautern
- Joshua Blake and ANOPP2 development team (NASA Langley)
  - ABEAT development and design optimization
- Nikolas Zawodny (NASA Langley)
  - LSAWT experiments and validation database generation

Conclusions

- Reviewed benefits of UAM vehicles to airspace
- Presented a gradient based design optimizations approach for UAM
- Outlined a methodology for validating optimization tools
- Showed selection of helically twisted rotor test in LSAWT as baseline
- Presented four optimization tools of differing fidelity and capability
- Outlined plan for future measurements in LSAWT of optimized designs

Acknowledgments

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